Development of a solid-state 100 mK refrigerator for user-supplied microelectronics

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Abstract

Solid-state refrigerators based on normal metal/insulator/superconductor (NIS) tunnel junctions are now a practical means of cooling from pumped ^{3}He bath temperatures to near 100 mK. While integration of NIS refrigerators with transition-edge sensors is underway, a more general-purpose cooling platform is desirable. We report on progress developing a NIS refrigerator designed to cool microelectronics devices on separate chips.

Keywords: micro-refrigerator; NIS junction; phonon cooling; refrigeration; tunneling
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1. Introduction

Advances in solid-state refrigerators based on Normal metal/Insulator/Superconductor (NIS) tunnel junctions have yielded fully lithographic devices with both a large temperature reduction and cooling power [1]. These solid-state refrigerators can operate at pumped ^{3}He bath temperatures of 300 mK and cool to near 100 mK. This capability is well suited to on-chip cooling for cryogenic devices that require 100 mK temperatures, such as thin-film sensors. Thin-film sensors operating near 100 mK provide unmatched sensitivity to incident energy, making them a likely technology for next-generation

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astronomical and analytical instruments [2]. The use of NIS refrigerators to cool cryogenic sensors is appealing in order to reduce the cost and complexity of traditional refrigeration techniques. A staged ^{3}He/NIS refrigerator could make 100 mK x-ray sensors much more accessible to both the scientific and industrial analytical communities.

NIS refrigerators utilize quantum-mechanical tunneling to remove the highest energy (hottest) electrons in the normal metal. This process cools the remaining electrons, while the phonons remain at the bath temperature due to the thermal decoupling between electrons and phonons at sub-Kelvin temperatures. In combination with a micro-machined Si_3N_4 membrane, NIS refrigerators cool not only the electrons in the normal metal, but also the phonons of the suspended membrane. We recently cooled a bulk neutron transmutation doped (NTD) germanium thermistor, with a volume 11,000 times larger than the refrigerating junctions, by gluing the NTD to a membrane cooled by NIS refrigerators [3].

We are currently working to integrate NIS refrigerators with an X-ray Transition-Edge-Sensor (TES) microcalorimeter for terrestrial material analysis. Together with Goddard Space Flight Center, we are also integrating NIS refrigerators with a millimeter-wavelength TES bolometer prototype for the Green Bank Telescope [4]. While combining the fabrication of the NIS refrigerators with a TES detector is the most straightforward way to cool thin-film sensors, it is not a flexible approach.

An alternative approach is to develop a NIS refrigerator designed to cool general user-supplied microelectronics. Such a cooling platform requires no foreknowledge of the payload to be cooled. We report on progress developing such a solid-state cooling platform.

2. Refrigerators

In order to provide a useful cooling platform, we needed a practical method for attaching the device to be cooled (payload) and making electrical connections. Gluing a payload to typical membranes is not practical because of the fragile membrane and extra thermal load from the macroscopic wire leads.

Our solution is to modify the micro-machined membrane. Traditionally, to make a square membrane, a solid square of substrate is etched away, creating a membrane much like a drum head. An alternative method is to etch away the substrate only at the perimeter of a square, creating a channel around the membrane, which will be referred to as a channel-etch. A channel-etched membrane is still suspended at the perimeter, but the original substrate is left in the middle. When placed on a flat surface, the membrane is supported by the substrate pillar in the middle and is no longer vulnerable to downward forces. We may then easily attach microelectronics and even wire bond directly on the membrane.

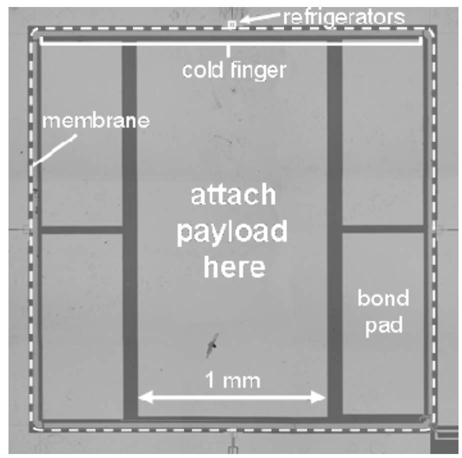

Fig. 1 - Optical micrograph of NIS cooling platform. Four pairs of NIS junctions (solid white rectangles at top), each 15 μm x 25 μm, are used to refrigerate a 2 mm x 2 mm channel-etched Si_3N_4 membrane (dashed white outline). In the center of the membrane is a 1 mm x 2 mm space for attaching payloads.

A NIS cooling platform is shown in Fig. 1. Fabrication details and cooling explanations are given in previous reports [1,5]. The device shown is estimated to cool from 320 to 225 mK with a surplus cooling power (as defined in Ref. 3) of 40-80 pW.

Fig. 2 shows the steps required to attach a payload to a NIS refrigerator platform. The finished cooler platform is first attached to a carrier wafer with wax. In this configuration, the channel-etched membrane is rigidly supported and therefore robust. The payload is then glued onto the membrane (Fig. 2a). The payload is electrically connected by wirebonds to contact pads on the membrane (Fig. 2b), which have thin-film leads to contact pads at the edge of the refrigerator chip. Finally, the cooler platform is released from the carrier wafer by melting the wax and soaking in a solvent such as acetone (Fig. 2c). The membrane is left suspended with the payload attached, ready to be cooled by the NIS refrigerators.

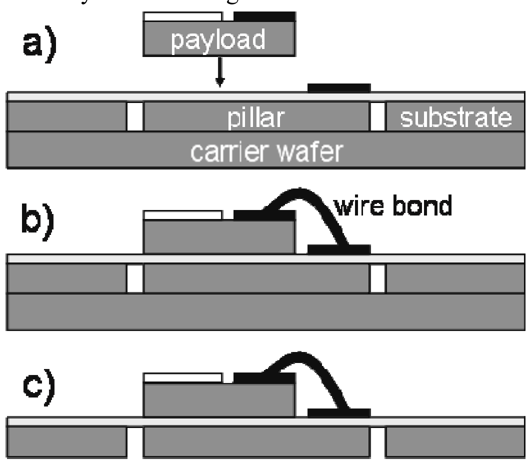

Fig. 2 – Side-view schematic showing series of steps needed to attach a payload to a NIS cooling platform.

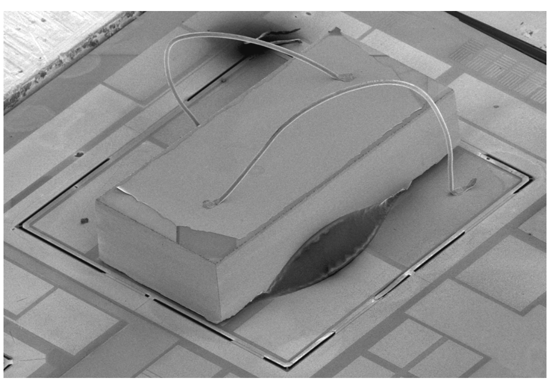

Fig. 3 – Scanning electron microscope image of a macroscopic 1 mm x 2 mm diced Si wafer (coated with a metal bilayer) glued to a NIS cooling platform. The bilayer has been wire bonded to bond pads on the membrane and the membrane has been released (Fig 2c).

Fig. 3 shows a test setup where the payload attached to the cooler platform is a 1 mm x 2 mm diced section of a Si wafer coated with a Mo/Cu bilayer. The attached bilayer is wire bonded to the contact pads on the membrane and the cooler platform has been released from the carrier wafer. Testing of this device is forthcoming.

3. Conclusion

We have developed a solid-state refrigerator based on NIS junctions that we can fabricate lithographically on a wafer scale, and that can cool user-supplied microelectronic devices on separate chips. We have successfully tested the channel-etch, payload attachment, wire bonding to the channel-etched membrane, and the membrane release. We will complete electrical tests in the near future.

Acknowledgments

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